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TECHNICAL NOTE

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THERMAL FATIGUE OF DUCTILE MATERIALS

III - BEHAVIOR OF CRUCIBLE 422 STEEL

By Francis J. Clauss

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

A study was made of the behavior of Crucible 422 steel in thermal fatigue and of the effect of constrained and free thermal cycling on the subsequent behavior in stress-rupture.

Specimens of Crucible 422 steel were alternately heated and cooled while constrained in a manner that prevented their free axial expansion and contraction, and the number of cycles to failure (cracking or fracture) was determined. The maximum cycle temperature (T_{max}) varied from 1000° to 1500° F, and the minimum cycle temperature was held constant at 200° F. Under these conditions the effect of T_{max} on the number of cycles to failure showed an abrupt change at a T_{max} of 1200° F. Cycling to T_{max} of 1200° F and above caused failures in less than 2000 cycles, while cycling to T_{max} below 1200° F did not cause any failures in less than 20,000 cycles. Considerable bulging of the specimens due to compressive creep occurred, however, at T_{max} of 1200° F and above.

Other specimens were removed from the thermal-fatigue apparatus before failure and subsequently tested in stress-rupture at 1100° F and 46,000 psi. Their behavior was compared with stress-rupture results for specimens subjected to identical temperature cycles but without constraint. Exposure to thermal fatigue or to thermal cycling alone in the absence of constraints significantly reduced the stress-rupture life.

Metallurgical changes caused by T_{max} were most significant in the thermal-fatigue behavior of Crucible 422 steel. During thermal cycling (constrained or free), the structure of tempered martensite undergoes further tempering and conversion to ferrite and spheroidized carbides, with an accompanying loss in hardness and stress-rupture strength.

INTRODUCTION

This study of the thermal-fatigue process in Crucible 422 steel extends earlier work on the precipitation-hardening austenitic alloys S-816 and Inconel 550 (refs. 1 and 2) to a ferritic steel hardened by the martensitic transformation. An important factor in the present investigation is the stability of the martensitic structure and its tendency to temper and lose strength during thermal cycling, either in the presence or absence of constraining forces.

The thermal-fatigue process was studied in reference 1 by alternately heating and cooling S-816 and Inconel 550 specimens that were constrained in a manner that prevented their free expansion and contraction. When heating and cooling were continued long enough, the specimens fractured, and the effect of different conditions of heating and cooling on the number of cycles to fracture was noted. For the conditions studied in reference 1, the following conclusions were drawn:

(1) The number of cycles to failure was more sensitive to changes in the maximum cycle temperature (T_{max}) than to changes in the temperature difference (T_{max} - T_{min})

(2) Increasing the time of exposure at high maximum cycle temperatures increased the number of cycles to fracture, whereas the same increase in time at low maximum cycle temperatures decreased the number of cycles to fracture

(3) The number of cycles to fracture depends on temperature and time effects in addition to the thermal strains absorbed by plastic flow in the materials

When thermal cycling was discontinued before the specimens had failed, the effect of the different conditions and number of cycles in thermal fatigue on the properties of the material could be measured. In reference 2, exposure to thermal-fatigue conditions had opposite effects on the subsequent creep-rupture strength of the two alloys: S-816 was strengthened, and Inconel 550 was weakened. Under the most damaging conditions studied, Inconel 550 lost 98 percent of its original creep-rupture life as a result of prior thermal fatigue, even though the number of cycles was only one-half of that required for failure by thermal fatigue alone. Under the same conditions, the creep-rupture life of S-816 was increased by about 50 percent. When the order of testing was reversed so that specimens were first exposed to creep-rupture conditions and then run to failure by thermal fatigue, the thermal-fatigue life of S-816 was sharply reduced, whereas that of Inconel 550 showed a slight increase.

The results of these two studies (refs. 1 and 2) were interpreted by extending existing theories of mechanical fatigue and creep-rupture to the thermal-fatigue process, and the role of structural changes was shown to be an important part of thermal-fatigue behavior. The process of thermal fatigue in S-816 and Inconel 550 was interpreted as occurring in the following two stages:

(1) A stage of strain- and/or precipitation-hardening, during which the ductility is reduced and the strength and hardness are increased

(2) A stage of the destruction of the cohesive bonds and the development and propagation of cracks

In the present study, tensile specimens of Crucible 422 steel were heated and cooled through various temperature cycles while they were constrained from expanding and contracting axially. Other specimens were exposed to identical cycles of heating and cooling but were not constrained. The maximum cycle temperature (T_{max}) to which the specimens were heated ranged from 1000° to 1500° F, and the minimum cycle temperature was 200° F in all cases. The range of T_{max} includes temperatures both above and below the maximum use temperature of Crucible 422 steel, which is about 1200° F. This range was chosen in order to investigate the effects of overheating at high T_{max} and to determine a lower limit of T_{max} below which thermal fatigue is unimportant.

The test cycles consisted of the following: (1) Heat 30 seconds to T_{max}, (2) hold 15 seconds at T_{max}, (3) cool 30 seconds to 200° F, (4) hold 15 seconds at 200° F and then repeat the cycle. The number of cycles to failure, changes in hardness, microstructural behavior, and stress-rupture properties were studied as a function of the conditions of thermal cycling. Stress-rupture tests were conducted at 1100° F and 46,000 psi, which gives a rupture life of about 200 hours for the as-heat-treated condition.

EQUIPMENT AND PROCEDURE

The equipment and procedure were the same as described in references 1 and 2. Figure 1 shows the configuration and dimensions of the specimens, and figure 2 shows the equipment used for holding the specimens during thermal cycling. Reference 1 discusses the degree of constraint imposed on the specimens during thermal cycling.

The material studied was Crucible 422 steel, which is a martensitic material of the following nominal composition:

	Alloying elements, percent by weight						
C	Mn	Si	Cr	Mo	W	V	Ni
0.18 to 0.25	1.00 max.	1.00 max.	11.5 to 14.0	0.75 to 1.25	0.75 to 1.25	0.15 to 0.40	0.50 to 1.00

The steel was obtained from a single heat in the form of 5/8-inch-diameter bar stock. This was cut into $5\frac{1}{2}$-inch lengths, which were austenitized at 1900° F for 1/2 hour and oil-quenched, then tempered at 1200° F for 2 hours and air-cooled to produce a structure of tempered martensite. This is a standard heat treatment for Crucible 422 steel. Figure 3 shows the microstructure of the steel in the as-received, quenched, and quenched and tempered conditions. Hardnesses were as follows:

Condition	Hardness, Rockwell -
As received	B 91
Quenched from 1900° F	C 54 to 55
Quenched and tempered	C 34

Test specimens were machined from the $5\frac{1}{2}$-inch lengths of bar stock after heat treatment. The specimens were numbered according to their positions in the bars, beginning with number 1 at one end of the bars and ending with number 30 at the opposite ends. All specimens were taken from two bars; specimen numbers are prefixed with the letter A or C, according to the bar from which they were taken.

The minimum cycle temperature was constant at 200° F for all tests, and the total time for each cycle of heating and cooling was $1\frac{1}{2}$ minutes (30 sec heat to T_{max}, 15 sec hold at T_{max}, 30 sec cool to 200° F, 15 sec hold at 200° F, then repeat). The specimens were held loosely in the test rig while the initial adjustments were made, and were then gripped tightly in a strain-free condition while at T_{max}. This induced the maximum tensile stress in the specimen on cooling. Thereafter, the specimens cycled between compressive stresses at T_{max} and tensile stresses at 200° F.

Cracking in the test section was presumed to have begun when the temperature record indicated that T_{max} started increasing from its set value. This presumption was based on the fact that a crack would reduce the current-carrying cross section and result in overheating. Fracture was defined as complete separation of the specimens in the test sections. The number of cycles to cracking was difficult to determine accurately, and the number of cycles to fracture was undoubtedly influenced by overheating after cracking had begun.

RESULTS AND DISCUSSION

Effect of Cycling Conditions on Number of Cycles to Failure

Results for the effect of varying the maximum cycle temperature on the number of cycles to failure are listed in table I and plotted in figure 4. The dashed curve in figure 4 represents the approximate number of cycles to fracture for specimens from bar C. All three specimens from bar A lasted considerably longer than did specimens from bar C that were thermally fatigued under the same conditions. This bar-to-bar variation for specimens from the same heat of material was larger than was expected from the normal scatter in fatigue results and high-temperature behavior. Bars A and C both had similar microstructures and hardnesses, although it may be significant that bar C had a slightly greater rupture life and lower ductility than bar A in stress-rupture tests at 1100° F and 46,000 psi.

Curves for the behavior of S-816 and Inconel 550 (ref. 1) are plotted in figure 4 for comparison with Crucible 422 steel, and it is clear that the behavior of Crucible 422 steel is quite different from that of the high-temperature "superalloys." The curve for Crucible 422 steel shows a sharp break at 1200° F; at T_{max} of 1200° F and above, all specimens from bar C fractured in less than 2000 cycles, whereas no fractures were obtained below 1200° F in less than 20,000 cycles. In fact, only one specimen cycled at a T_{max} below 1200° F was cycled to complete fracture; all others were removed from the test rig after 20,000 cycles or more and tested in stress-rupture. As T_{max} was lowered from 1500° to 1200° F, thermal-fatigue life gradually increased. The rate of increase for Crucible 422 steel was comparable with that for S-816 between 1600° and 1400° F.

Photographs of the fractured specimens and photomicrographs of the microstructure in the area of the fractures are shown in figure 5. Between T_{max} of 1500° and 1200° F, a considerable amount of bulging occurred in the centers of the test sections. This bulging was due to creep in compression while the specimens were heated at or near T_{max}. Fractures occurred in the areas immediately adjacent to the bulged sections, and the bulged sections showed considerable cracking, which is

visible in the photographs. Considerable void formation immediately below the fractured edges is also evident in the photomicrographs. In some cases (e.g., specimen C-17, fig. 5(d)) the fracture started from opposite sides of the areas at either end of the bulged section; complete fracture occurred when these were joined by a longitudinal fracture along the central plane, as in specimen C-29 of figure 5(e). Only one specimen was tested to failure at a T_{max} below 1200° F; this specimen (tested at a T_{max} of 1100° F) showed no bulging and fractured in a brittle manner. Nor was any bulging evident in the remaining specimens run to 20,000 or more cycles (but not fractured) at T_{max} less than 1200° F.

The microstructure of the specimen fractured by cycling at a T_{max} of 1500° F contained areas of martensite (VDPHN = 246), as in figure 5(a), and other areas of fine grains of ferrite with fine carbide particles (VDPHN = 188) (not shown). For T_{max} from 1450° to 1200° F the final microstructure contained fine grains of ferrite and carbide particles, with VDPHN of about 200. At a T_{max} of 1100° F, the structure of the metal in the area of fracture was tempered martensite with VDPHN of 230. What appears to be decarburization along the fractured edges of some of the photomicrographs is actually due to rounding-off of the edges during polishing. Examination at high magnifications indicated that fractures were transcrystalline.

At T_{max} of 1200° F and above, failures in thermal fatigue appear to be due to a general weakening and deterioration of Crucible 422 steel associated with the conversion of the martensitic structure to ferrite and cementite. Failures occurred in necked-down regions where the stresses were greatest. Cracks propagated slowly, and a rather large number of cycles was required from the time that cracks were first apparent to the time of complete fracture. At a T_{max} of 1100° F, thermal fatigue occurred in a more normal, brittle manner and, as shown by the stress-rupture results in the following section, the rate of weakening was considerably less than at the higher T_{max}.

Effect of Prior Thermal Fatigue or Thermal Cycling on Stress-Rupture Behavior

Table II(a) summarizes the results of stress-rupture tests made on specimens from bar C that had been exposed to varying amounts and conditions of thermal fatigue from T_{max} of 1000° to 1175° F. Although no thermal-fatigue failures occurred in less than 20,000 cycles at T_{max} less than 1200° F, stress-rupture strength was materially reduced. For example, 20,000 cycles between 1150° and 200° F reduced the stress-rupture life to almost one-tenth of that for material in the as-heat-treated condition. For lower T_{max} the loss in strength was less, so that cycling 20,030 times between 1050° and 200° F reduced the stress-rupture life to about one-half of that for material in the as-heat-treated condition. At a T_{max} of 1000° F there was no loss in strength even after 27,432 cycles.

Ductility, as measured by the reduction in area at the fracture, was decreased by prior thermal fatigue; the decrease in ductility ran parallel to the decrease in strength and was greatest for the specimen cycled to a T_{max} of 1150° F (specimen C-21). Thermal fatigue does not actually embrittle this material, however, since all fractures were very ductile.

Table II(b) summarizes the results of stress-rupture tests made on specimens from bar A that had been exposed to varying amounts and conditions of thermal fatigue from T_{max} of 1150° to 1300° F. Exposure to thermal fatigue at a T_{max} of 1300° F resulted in an almost complete loss of rupture life after only a very few cycles. The same was true for 900 cycles at a T_{max} of 1250° F. Even at 1200° F there was a loss of about one-third of the original rupture life after 450 cycles, which is only about 4 percent of the thermal-fatigue life, and this loss increased with increasing numbers of cycles. At 1150° F the material was not weakened to about 1350 cycles of prior thermal fatigue; as the number of cycles at 1150° F increased, however, the rupture life decreased. In general, then, Crucible 422 steel suffers a marked loss in rupture strength because of exposure to thermal fatigue at T_{max} of 1150° F and above. The higher the T_{max}, the more rapidly strength decreases.

From the results on specimens from bars A and C, the number of cycles in thermal fatigue that will reduce the stress-rupture life to one-half that of the as-heat-treated condition varies with T_{max} approximately as follows:

T_{max}, °F	Number of cycles
1300	<50
1250	500
1200	800
1150	1,500
1050	20,000

These estimates are based on a minimum cycle temperature of 200° F and 30-15-30-15-second cycles of heating and cooling, for stress-rupture testing at 1100° F and 46,000 psi. Under these stress-rupture conditions, the rupture life of Crucible 422 steel in the as-heat-treated condition is about 200 hours.

The ductility of the thermally cycled specimens from bar A remained high, as shown by the reductions in area at fracture listed in table II(b).

A few results for thermal cycling without constraint are listed in table III. These specimens were exposed to the same temperature conditions as those in table II(b), but they were not constrained by the test rig and were therefore free to expand and contract during thermal cycling. Results show that thermal cycling alone is sufficient to weaken Crucible 422 steel. Even thermal cycling to a T_{max} of 1150° F, which is below

the normal tempering temperature used in heat-treating the steel, is sufficient to lower the stress-rupture life markedly after 1350 cycles.

The tests without constraint indicate that the rapid reduction in strength at higher T_{max} is primarily caused by tempering of the original martensite and its conversion to ferrite and cementite and that this can occur during thermal cycling alone in the absence of constraint or probably by simply prolonged heating. There is nothing unexpected in these structural changes or in the loss of strength due to heating Crucible 422 steel to temperatures higher than 1150° or 1200° F, though no quantitative data are available to indicate the extent of this damage for different times and temperatures. Although temperature alone is sufficient to cause these changes, the presence of strains (either those due to constrained temperature changes or to external loads) can probably accelerate them and probably become more important at lower temperatures (i.e., lower values of T_{max}). It is significant that even at 1050° F, which is well below the tempering temperature or the maximum use temperature of 1200° F for this material, the stress-rupture life can be cut in half by 20,000 cycles (approximately 83 hr at T_{max}) in thermal fatigue. No tests were conducted to indicate the amount by which the stress-rupture life would have been reduced by 20,000 cycles to 1050° F in the absence of constraint or by an equivalent period of continuous and unconstrained heating at 1050° F.

CONCLUDING REMARKS

A study was made of the thermal-fatigue behavior of Crucible 422 steel after cycling between maximum temperatures from 1000° to 1500° F and a minimum temperature of 200° F on 30-15-30-15-second cycles of heating and cooling. Stress-rupture tests were conducted at 1100° F and 46,000 psi, under which conditions the rupture life of material in the as-heat-treated condition is about 200 hours. The results indicate the following:

The effect of T_{max} on the number of cycles to failure shows an abrupt change at a T_{max} of 1200° F. Cycling to T_{max} of 1200° F and above caused failures (both cracking and fracture) in less than 2000 cycles, with the number of cycles to failure decreasing slowly as T_{max} was increased. Considerable bulging due to compressive creep occurred, however, in this temperature range. Cycling to T_{max} below 1200° F did not cause any failures in less than 20,000 cycles. Cycling appreciably beyond 20,000 cycles was not investigated.

Prior exposure to thermal fatigue with T_{max} in the range of 1050° to 1300° F reduced the stress-rupture life of Crucible 422 steel at 1100° F and 46,000 psi. The approximate number of cycles of thermal

fatigue required to reduce the rupture life to one-half that of the as-heat-treated condition varied with T_{max} as follows:

T_{max}, °F	Number of cycles
1300	<50
1250	500
1200	800
1150	1,500
1050	20,000

Although maximum cycle temperatures of 1150° and 1050° F did not result in fracture in 20,000 cycles, it is of interest that exposure to these conditions did cause significant reductions in stress-rupture life. The one test run with a T_{max} of 1000° F indicated no damage to stress-rupture life after 27,000 cycles.

At maximum cycle temperatures of 1150° F and above, thermal cycling alone in the absence of constraints also reduced rupture life, and it is probable that continuous and unconstrained heating for equivalent periods of time would have had the same effect. The reduction in rupture life in this range was undoubtedly the result of changes in the metallurgical structure caused primarily by temperature alone and was not significantly effected by constraining the specimens during thermal cycling. The effect of thermal cycling alone (without constraint) was not investigated below 1150° F. At lower maximum cycle temperatures, where the martensitic structure is more stable, the cyclic strains during constrained heating and cooling may be important in accelerating structural changes that would occur more slowly during temperature exposure alone.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, July 2, 1959

REFERENCES

1. Clauss, Francis J., and Freeman, James W.: Thermal Fatigue of Ductile Materials. I - Effect of Variations in the Temperature Cycle on the Thermal-Fatigue Life of S-816 and Inconel 550. NACA TN 4160, 1958.

2. Clauss, Francis J., and Freeman, James W.: Thermal Fatigue of Ductile Materials. II - Effect of Cyclic Thermal Stressing on the Stress-Rupture Life and Ductility of S-816 and Inconel 550. NACA TN 4165, 1958.

TABLE I. - EFFECT OF VARYING MAXIMUM CYCLE TEMPERATURE (T_{max})

ON NUMBER OF CYCLES TO FAILURE AND HARDNESS

[Minimum cycle temperature, 200° F in all cases;

30-15-30-15-second cycles of heating and cooling.]

T_{max}, °F	Specimens from bar C				Specimens from bar A		
	Number of cycles to -		Hardness,[a] VDPHN	Specimen	Number of cycles to -		Specimen
	Cracking	Fracture			Cracking	Fracture	
1500	--------	561	188 To 246	C-14			
1450	960	1,035	200	C-1			
1400	690	971	183	C-23			
1350	990	[b]1,105	205	C-17			
1300	1,390	1,750	210	C-29	3,210	3,713	A-22
1250	1,273	1,685	204	C-18	3,628	3,812	A-10
1200	1,700	1,835	207	C-27	11,950	12,269	A-1
1175	>[c]7,430	-------		C-8			
1150	>[d]20,000	-------		C-21			
1100	>[d]20,236	-------		C-12			
1100	20,700	21,038	230	C-13			
1050	>[d]20,030	-------		C-2			
1000	>[d]27,432	-------		C-4			

[a]Hardness of tempered martensite (as-heat-treated condition) was 330 VDPHN.

[b]Removed before complete fracture.

[c]Test discontinued because of equipment failure; no cracking or fracture; specimen removed for stress-rupture test.

[d]No cracking or fracture; specimen removed for stress-rupture test.

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TABLE II. - EFFECT OF VARIOUS CONDITIONS AND AMOUNTS OF THERMAL FATIGUE ON SUBSEQUENT STRENGTH AND DUCTILITY IN STRESS-RUPTURE

(a) Specimens from bar C

Specimen	Thermal cycling prior to stress-rupture evaluation		Stress-rupture behavior at 1100° F and 46,000 psi	
	T_{max}, °F	Number of cycles[a]	Life, hr	Reduction in area, percent
C-5 C-20	----	None (as heat treated)	236.0 201.9 Av. 219.0	67.9 69.1 68.5
C-8	1175	7,430	21.7	67.8
C-21	1150	20,000	24.3	53.8
C-6	1100	10,320	138.0	67.0
C-12	1100	20,236	95.1	64.1
C-2	1050	20,030	109.7	67.5
C-4	1000	27,432	250.9	67.6

[a]Cycles consist of heating to T_{max}, holding, cooling to 200° F, and holding for 30, 15, 30, and 15 seconds, respectively.

TABLE II. - Concluded. EFFECT OF VARIOUS CONDITIONS AND AMOUNTS OF THERMAL FATIGUE ON SUBSEQUENT STRENGTH AND DUCTILITY IN STRESS-RUPTURE

(b) Specimens from bar A

Specimen	Thermal cycling prior to stress-rupture evaluation		Stress-rupture behavior at 1100° F and 46,000 psi	
	T_{max}, °F	Number of cycles[a]	Life, hr	Reduction in area, percent
A-28	----	None	195.9	72.1
A-29		(as heat treated)	170.0	70.9
			Av. 183.0	71.5
A-30	1300	58	1.2	74.2
A-19	↓	450	.15	72.2
A-23	1250	450	115.0	63.9
A-15	↓	900	.3	72.1
A-13	1200	450	124.5	71.9
A-5	↓	900	94.25	69.0
A-17	1150	450	177.1	72.1
A-7		900	209.4	70.5
A-27		1350	148.9	71.3
A-2	↓	3000	.2	71.3

[a]Cycles consist of heating to T_{max}, holding, cooling to 200° F, and holding for 30, 15, 30, and 15 seconds, respectively.

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TABLE III. - EFFECT OF VARIOUS CONDITIONS AND AMOUNTS OF THERMAL CYCLING WITHOUT CONSTRAINT ON SUBSEQUENT STRENGTH AND DUCTILITY IN STRESS-RUPTURE FOR SPECIMENS FROM BAR A

Specimen	Thermal cycling prior to stress-rupture evaluation		Stress-rupture behavior at 1100° F and 46,000 psi	
	T_{max}, °F	Number of cycles[a]	Life, hr	Reduction in area, percent
A-16	1300	450	1.05	73.8
A-24	↓	900	.45	73.7
A-6	↓	1350	1.9	74.2
A-21	1200	900	102.5	66.8
A-9	↓	1350	9.6	69.6
A-11	1150	1350	144.9	65.8

[a]Cycles consist of heating to T_{max}, holding, cooling to 200° F, and holding for 30, 15, 30, and 15 seconds, respectively.

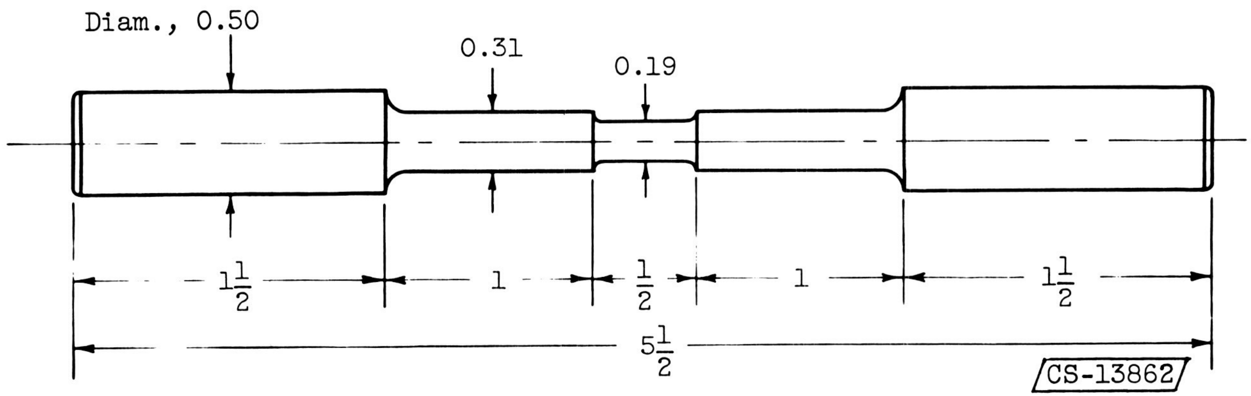


Figure 1. - Test specimen. (All dimensions in inches.)

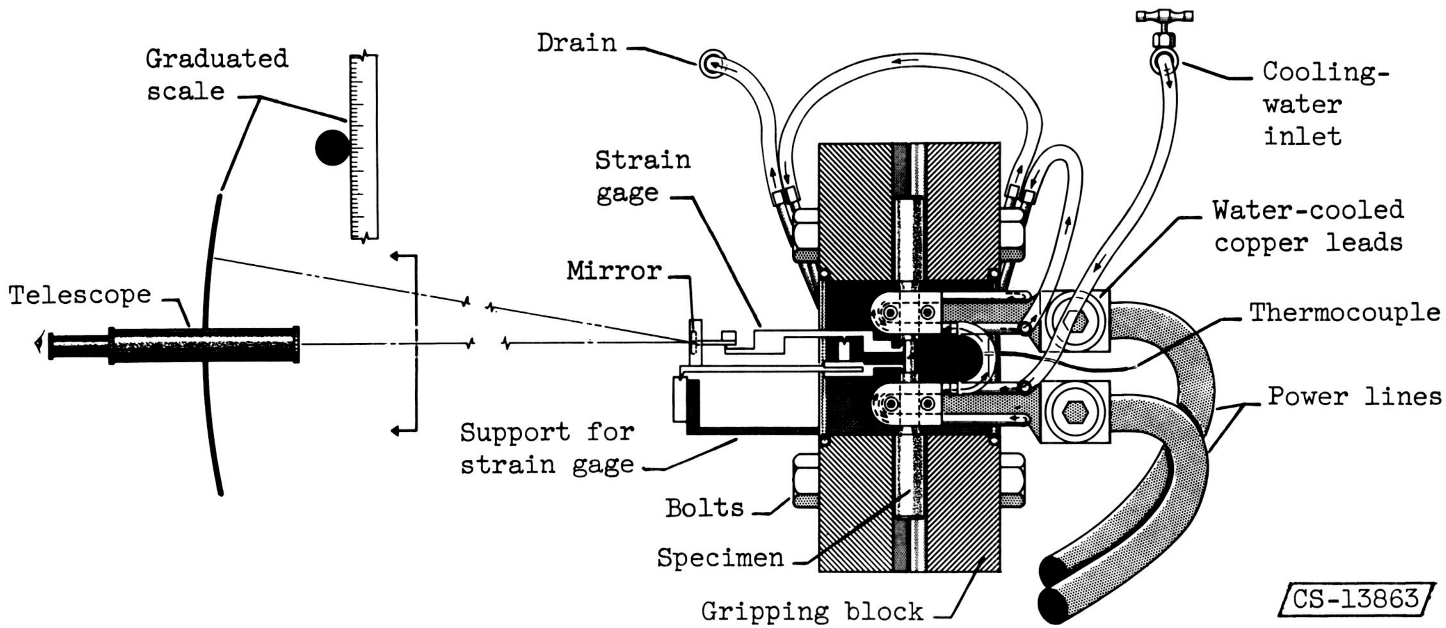
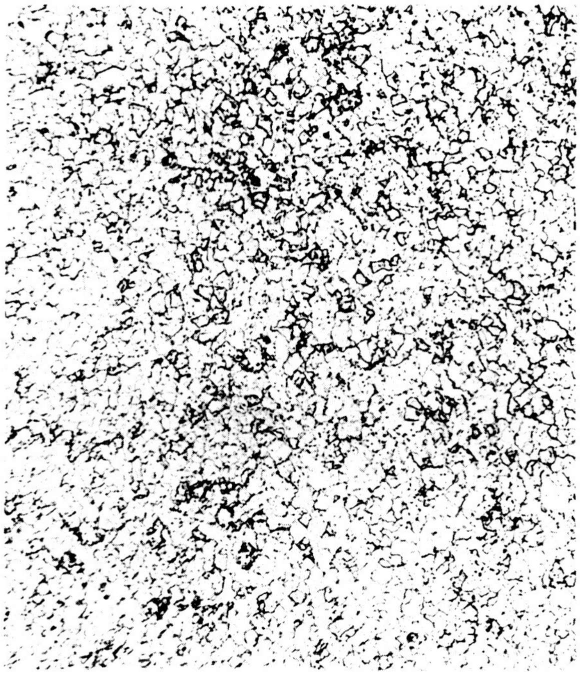


Figure 2. - Thermal-fatigue apparatus.



(a) As received; hardness, Rockwell B 91.

(b) Quenched from 1900° F; hardness, Rockwell C 54 to 55.

(c) Quenched and tempered; hardness, Rockwell C 34.

Figure 3. - Microstructure of Crucible 422 steel. Vilella's martensitic etch; X250.

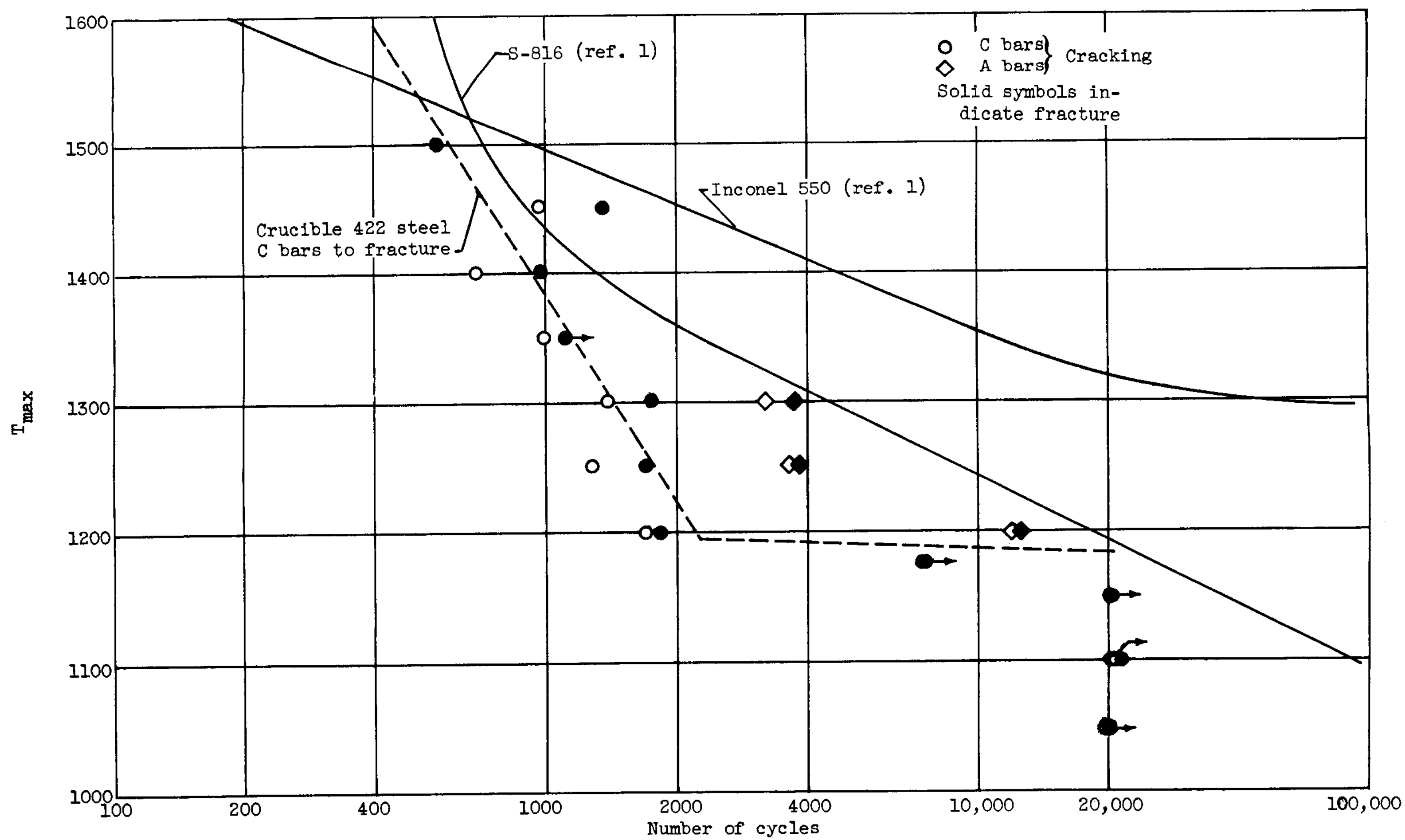


Figure 4. - Effect of maximum cycle temperature T_{max} on number of cycles to failure for crucible 422 specimens thermally cycled at a constant minimum cycle temperature of 200° F; 30-15-30-15-second cycle.

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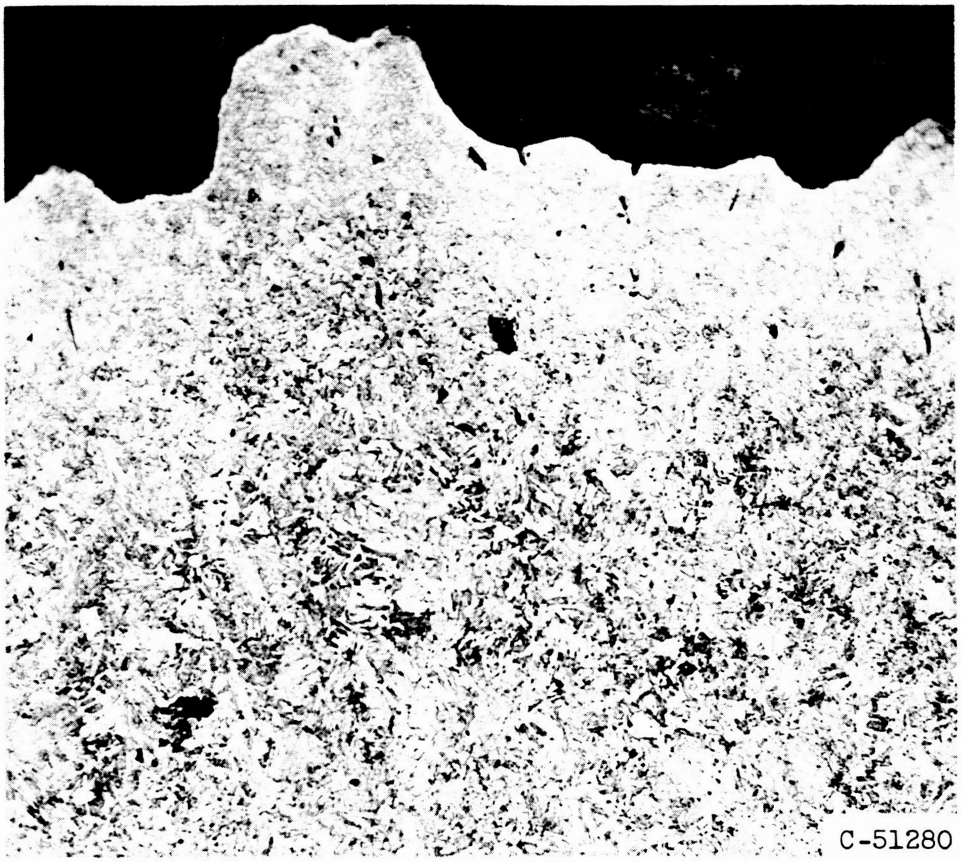
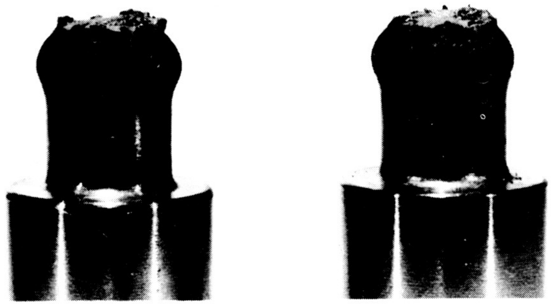


C-51280

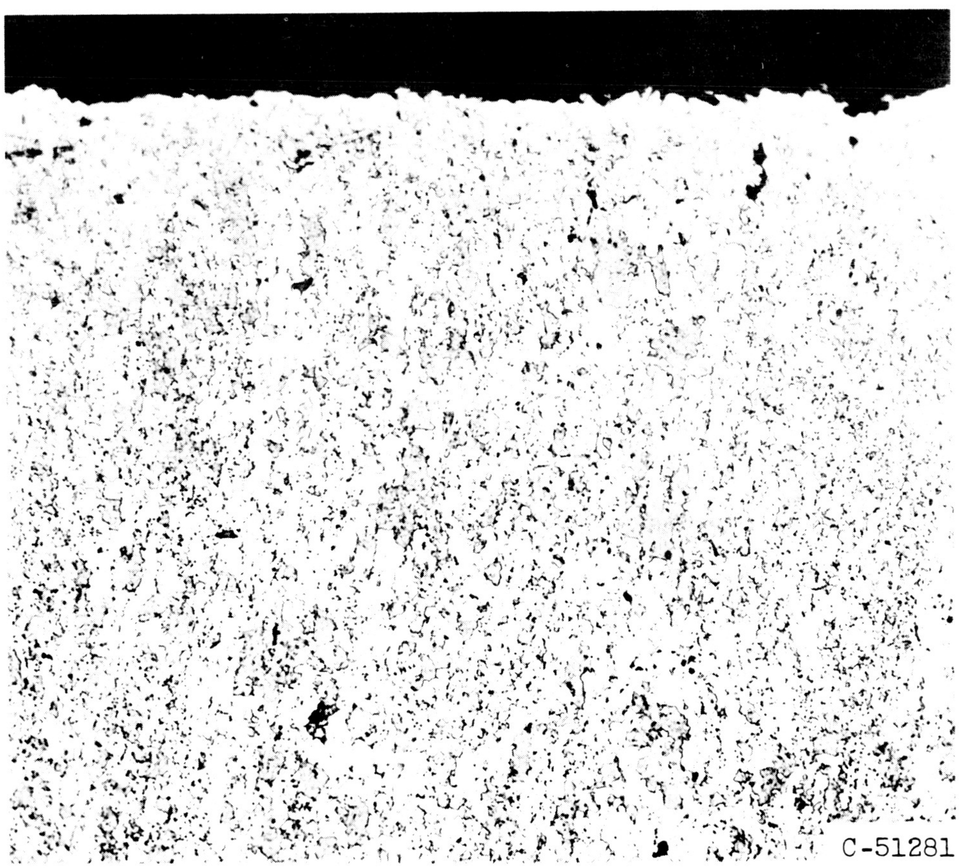
Etched; X250

(a) Specimen C-14; 561 cycles to fracture at 1500°/200° F.

Figure 5. - Fractured Crucible 422 specimens and microstructure in area of fracture.



C-48560

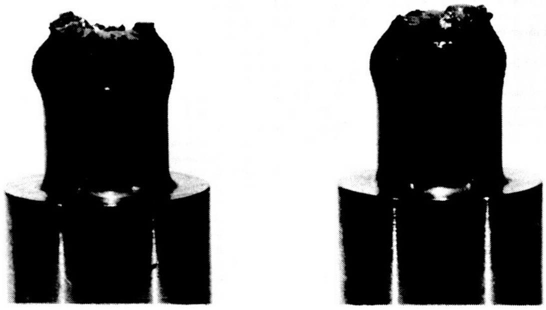


C-51281

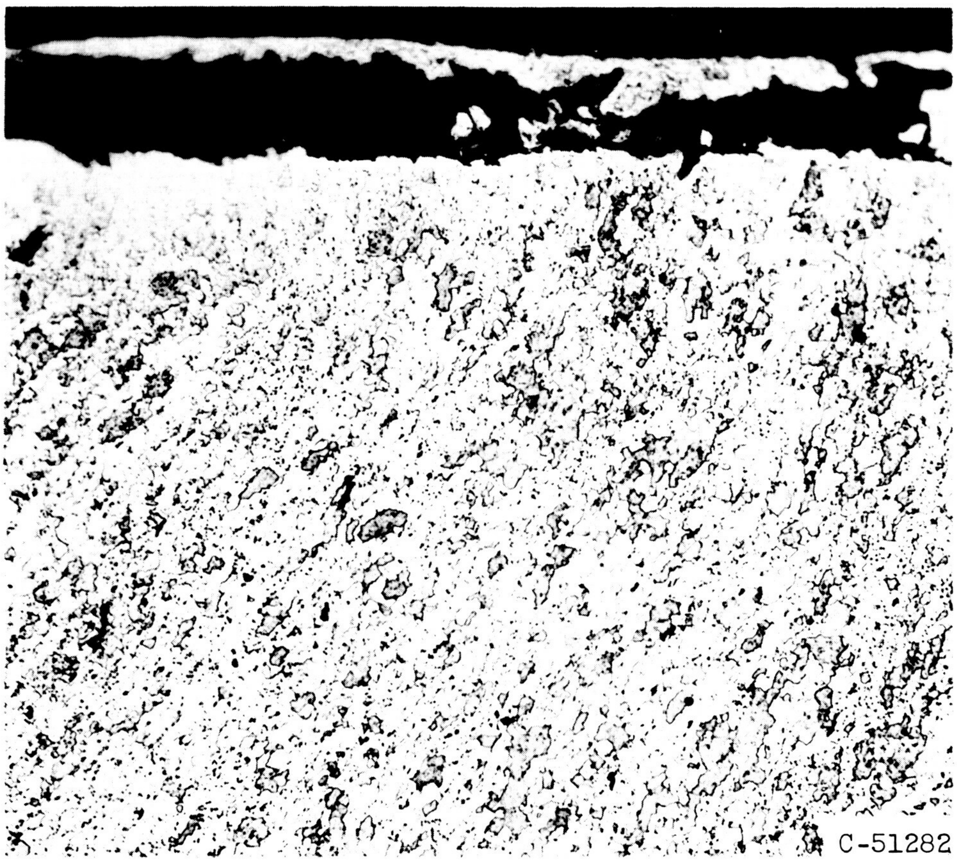
Etched; X250

(b) Specimen C-1; 1035 cycles to fracture at 1450°/200° F.

Figure 5. - Continued. Fractured Crucible 422 specimens and microstructure in area of fracture.



C-48558



C-51282

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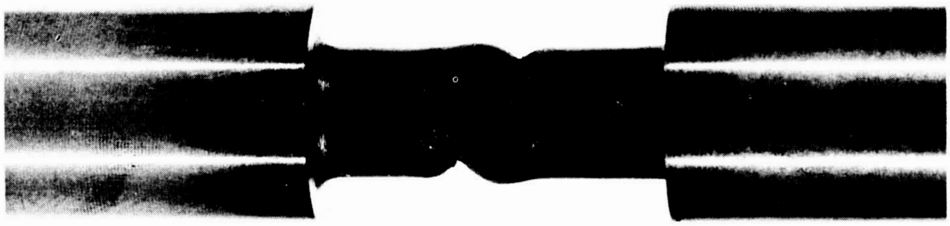
(c) Specimen C-23; 971 cycles to fracture at 1400°/200° F.

Figure 5. - Continued. Fractured Crucible 422 specimens and microstructure in area of fracture.



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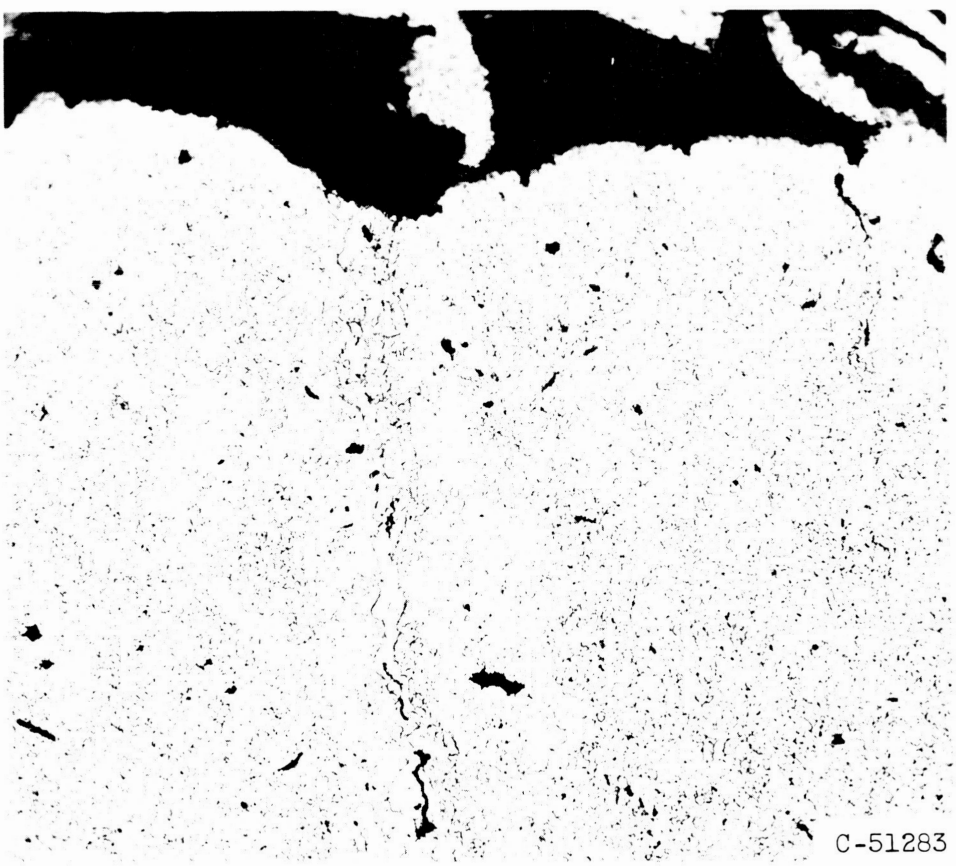


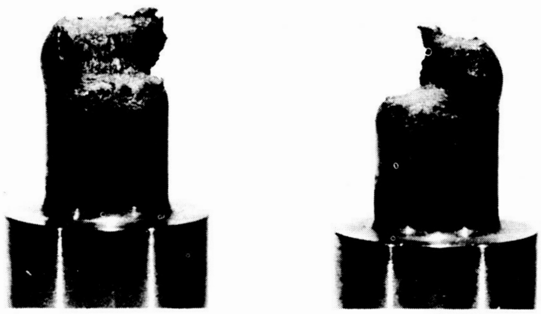
C-51283

Etched; X250

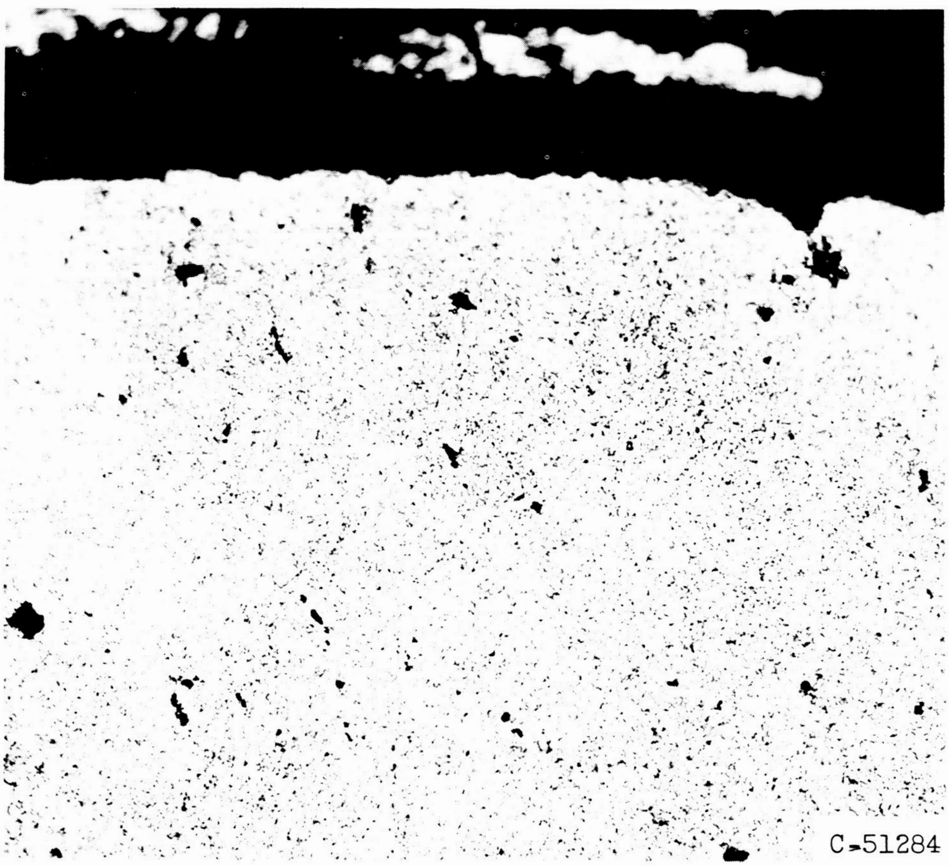
(d) Specimen C-17; not fractured after 1105 cycles at 1350°/200° F.

Figure 5. - Continued. Fractured Crucible 422 specimens and microstructure in area of fracture.

E-359



C-48559

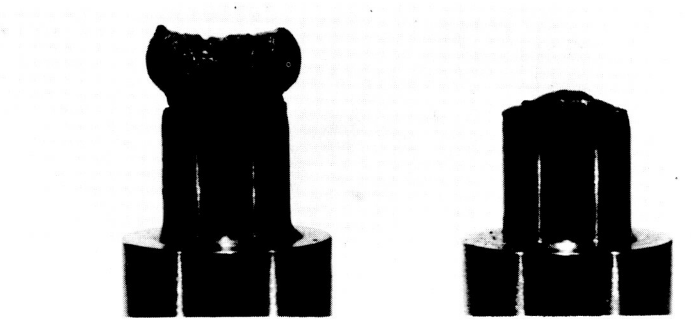


C-51284

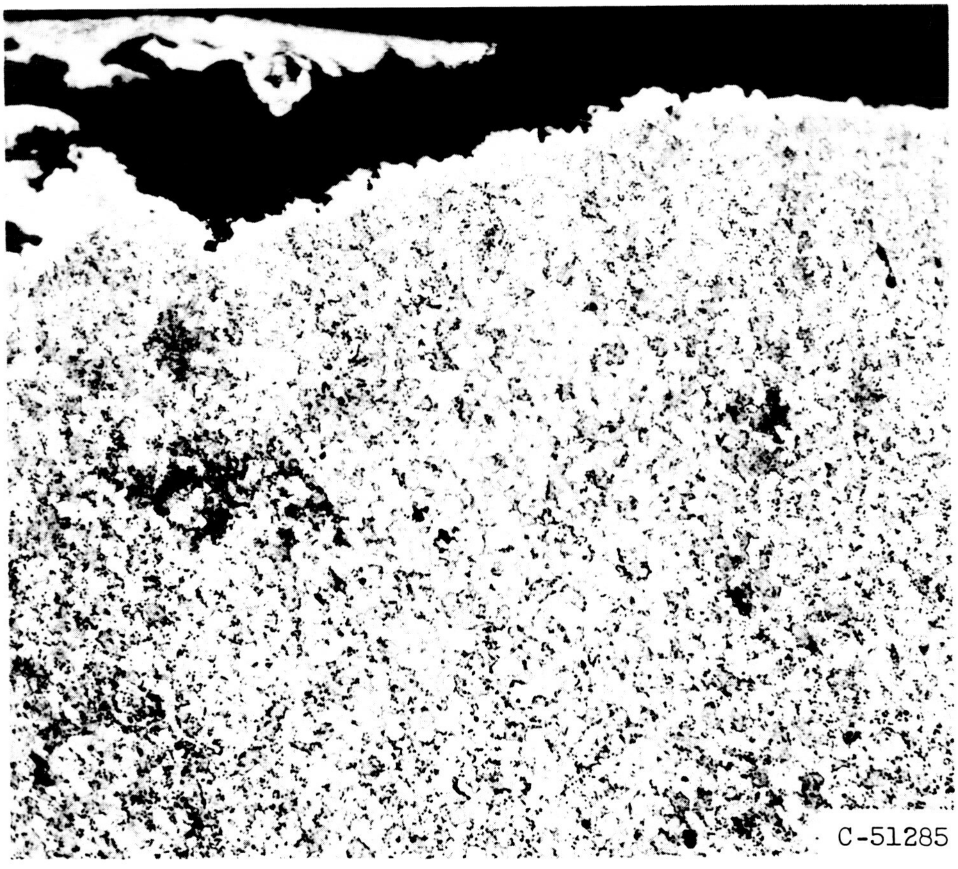
Etched; X250

(e) Specimen C-29; 1750 cycles to fracture at 1300°/200° F.

Figure 5. - Continued. Fractured Crucible 422 specimens and microstructure in area of fracture.



C-48556

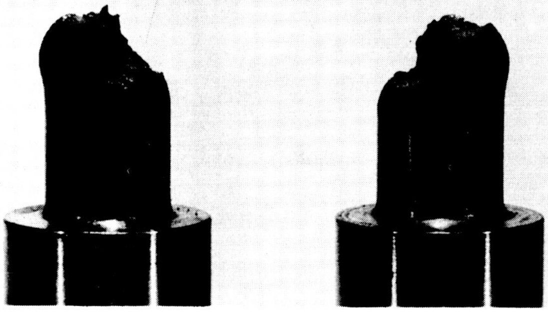


Etched; X250

(f) Specimen C-18; 1685 cycles to fracture at 1250°/200° F.

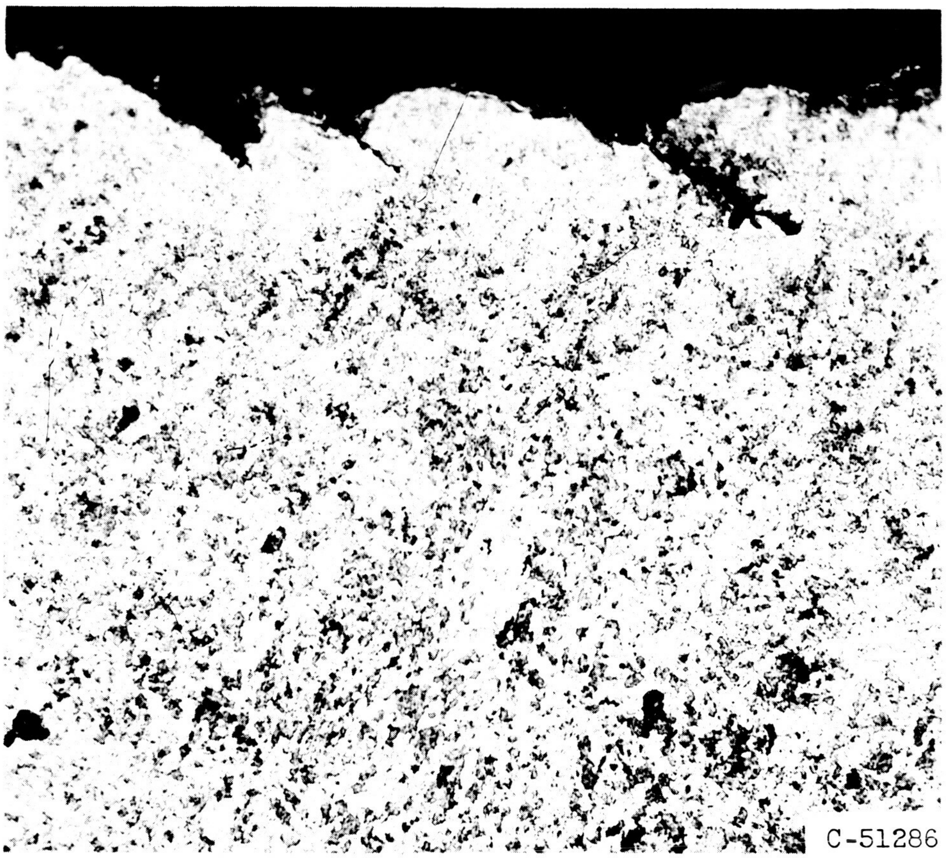
Figure 5. - Continued. Fractured Crucible 422 specimens and microstructure in area of fracture.

E-359



C-48555

E-359



C-51286

Etched; X250

(g) Specimen C-27; 1835 cycles to fracture at $1200^{\circ}/200^{\circ}$ F.

Figure 5. - Concluded. Fractured Crucible 422 specimens and microstructure in area of fracture.